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Original Research

Variability of Soil Physical and Chemical Properties across Contrasting Lithological Formations in Gombe State, Northeastern Nigeria

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Abstract

Lithology is one of the major factors influencing soil formation and variability, particularly over similar ecological conditions. This study evaluated the influence of different lithological formations on selected soil physicochemical properties across Gombe state, Nigeria. A detailed soil survey was conducted across ten (10) lithological units, namely Sandstone, Shale, Siltstone, Clay and Ironstone (SSSCI), Porphyritic Granite and Biotite (PGB), Shale and Mudstone (SMS), Limestone and Shale (LSS), Shale Limestone and Sandstone (SLSS), Basalt (BST), Shale, Sandstone and Limestone (SSL), Alluvium (ALV), Sandstone, Shale and Clay (SSC), and Sandstone, Siltstone and Shale (SSS). Twenty (20) profile pits were excavated and representative soil samples were collected from identified genetic horizon. The samples were taken to the laboratory for soil analysis. Results revealed that sand was the dominant particle-size fraction in all lithologies. Significant ($p < 0.05$) variations among lithologies were observed for sand, silt, clay, soil pH, organic carbon, exchangeable bases, base saturation and ECEC. Soils developed over PGB, BST and SSS contained the highest organic carbon (7.04, 6.82 and 6.52 g kg^{-1}) and total nitrogen (0.50, 0.50 and 0.38 g kg^{-1}), whereas soils on ALV and SSC recorded the lowest nutrient status. Total exchangeable bases and base saturation percentage were rated high and significantly higher ($p < 0.05$) in BST, SSL, SMS and SLSS derived soils, indicating greater nutrient reserves. Correlation analysis showed strong positive relationships among soil pH, total exchangeable bases, and organic carbon, while sand content exhibited significant negative correlations with most fertility parameters. The Principal Component Analysis shows that PC1 and PC2 explained 63.7% of the total variability with exchangeable bases, ECEC, soil pH, total nitrogen, base saturation, Electrical conductivity, organic carbon and soil texture being the principal factors driving soil differentiation. The study demonstrates that lithological variation exerts a significant influence on soil fertility in savanna regions. Consequently, the need for lithology-based soil management to support sustainable agricultural production in Gombe state.

1. Introduction

Soil heterogeneity reflects interactions among climate, organisms, relief, parent material and time. Lithology influences soil morphology, physical, chemical and mineralogical properties, creating spatial differences that complicate land management and crop production (Maccarthy *et al*., 2013). Parent material also affects nutrient dynamics, fertility and ecosystem functioning (Adhikari & Hartemink, 2016; Bouma *et al*., 2022). Lithology and landscape position have been associated with lateral and vertical soil variation in savanna environments (Maniyunda *et al*., 2013; Babalola *et al*., 2019; Solomon *et al*., 2022). In Nigeria, previous studies have focused on one or two parent materials or localized landscapes (Nwaoba *et al*., 2021). Research in northeastern Nigeria has largely emphasized characterization, classification and pedogenesis within individual settings, with fewer comparisons across lithological formations (Achukwu *et al*., 2020; Kefas *et al*., 2025). Consequently, regional evidence on lithological controls of soil properties and fertility remains limited. Savanna soils can lose fertility under continuous cultivation (Shehu *et al*., 2015), making assessment of parent-material differences important for precision farming and sustainable production (Afu *et al*., 2021; John *et al*., 2019).

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Evidence on lithosequence-related soil variability in Gombe State remains limited. An understanding of the variation in soil properties across lithologies will highlight the intrinsic differences in soils as well as the relationship between soils derived from different parent materials, thereby suggesting site-specific management practices for sustainable crop production. The study advances current knowledge by quantifying lithological impact on soil variability, identifying key soil quality indicators associated with contrasting parent materials, and establishing a regional baseline for digital soil mapping, lithology-specific nutrient management, sustainable land-use planning, and climate-smart agriculture in northeastern Nigeria. This study provides an integrated assessment of soils developed over ten lithological units using standardized field and laboratory procedures. Therefore, this research was carried out to evaluate the variation in soil properties as influenced by different lithological formations, to examine the relationships within the soil properties and to identify principal soil properties responsible for differentiation among lithological formations.

2. Materials and Methods

2.1 Study area

The study covered Gombe State, northeastern Nigeria, located between approximately between 10°35′30″ and 11°50′30″ N and 09°28′00″ and 11°20′30″ E (Figure 1). The state has river-basin, plain, upland and highland terrain. Elevation ranges from about 184 m in the Gongola River basin to 1,184 m in the highlands. The climate has distinct wet and dry seasons; records for 1977–2017 indicate annual rainfall of 527.4–853 mm and mean annual temperatures of 25.7–29.3 °C. Relative humidity peaks in August and falls below 10% during the harmattan (Abashiya *et al*., 2017; Bello *et al*., 2020). Geological formations include alluvium, Kerri Kerri, Gombe, Pindiga, Yolde and Bima formations, as well as basement-complex rocks. Vegetation is Sudan/Savanna woodland with scattered shrubs, trees and grasses (Balzerek *et al*., 2003). Major land-cover classes include rain-fed agriculture/grazing, irrigated land, swamps, settlements, woodland and water bodies. Grassland and shrubland cover much of the state and support farming and livestock production (Ikusemoran *et al*., 2018). The state's extensive agricultural and grazing lands support grain production and livestock rearing and contribute to its role as an important grain-producing area in northeastern Nigeria (Ikusemoran *et al*., 2018). Ten lithological units were mapped: Sandstone, Shale, Siltstone, Clay and Ironstone (SSSCI; approximately 2,734.61 ha); Porphyritic Granite and Biotite (PGB; 18.56 ha); Shale and Mudstone (SMS; 299.14 ha); Limestone and Shale (LSS; 439.22 ha); Shale, Limestone and Sandstone (SLSS; 1,390.76 ha); Basalt (BST; 15.64 ha); Shale, Sandstone and Limestone (SSL; approximately 590.36 ha); Alluvium (ALV; 130.21 ha); Sandstone, Shale and Clay (SSC; 7,541.01 ha); and Sandstone, Siltstone and Shale (SSS; 3,973.85 ha). These units occur across several local government areas and represent diverse parent materials relevant to soil formation and variability.

2.2 Remote sensing and GIS-based lithological delineation

Lithological units were delineated using a cloud-free Landsat 8 Operational Land Imager scene, existing geological information and field observations. Multispectral bands have 30 m resolution and the panchromatic band 15 m. Imagery was pre-processed, projected to UTM/WGS 84, and examined using band combinations and ratios from visible, near-infrared and shortwave-infrared bands to enhance contrasts among exposed materials. The imagery was clipped to the state boundary and integrated with the available geological map in a GIS. The map was georeferenced, lithological boundaries digitized, and preliminary boundaries checked against imagery and field coordinates. The resulting map guided sampling and assignment of profiles to lithological units.

2.3 Field work/soil sampling

A detailed soil survey was conducted at 1:25,000 scale. The georeferenced base map was uploaded to a GPS, and two profile pits were excavated in each of the ten lithological units, giving 20 profiles (Figure 1). Samples were collected from genetic horizons following Soil Survey Staff (2014), labelled and transported to the laboratory. Twenty surface and 20 subsurface samples were analysed, giving 40 samples.

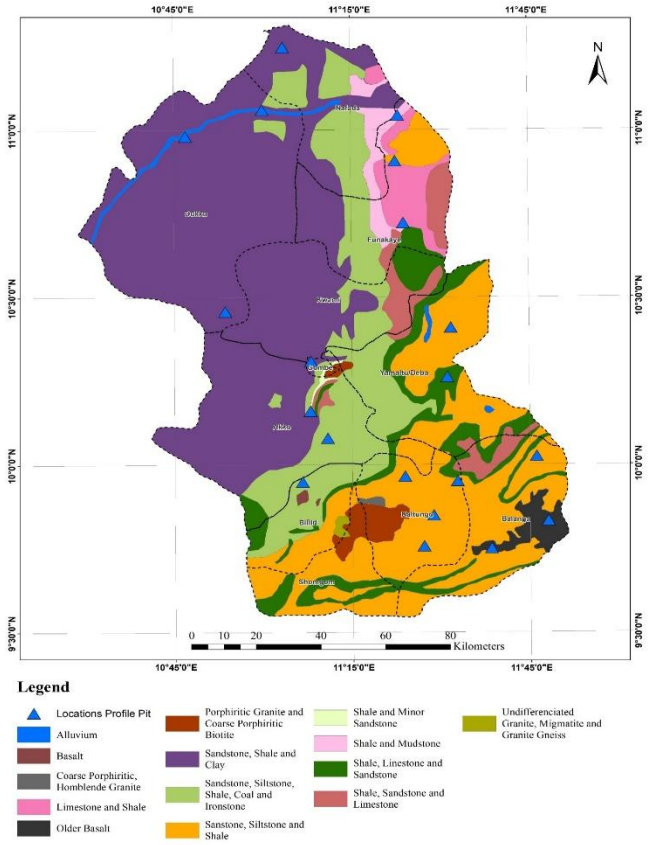

Figure 1. Lithological map of Gombe State.
Source: Modified from Ikusemoran *et al*. (2018).

2.4 Laboratory analysis

Samples were air-dried, gently crushed and passed through a 2-mm sieve. Particle-size distribution was determined by the hydrometer method; bulk density by the core method; pH in water using a glass-electrode meter; and electrical conductivity (EC) in a 1:2 soil-to-water extract (Agbenin, 1995; Blake & Hartge, 1986). Organic carbon was measured by Walkley–Black wet oxidation (Nelson & Sommers, 1982), available phosphorus by Bray I, and total nitrogen by Kjeldahl digestion (Agbenin, 1995; Bremner & Mulvaney, 1982). Exchangeable Ca, Mg, K and Na were extracted with 1 N neutral ammonium acetate. Ca and Mg were measured by atomic absorption spectrophotometry and K and Na by flame photometry. Total exchangeable bases (TEB) were calculated as the sum of exchangeable bases. Exchangeable acidity was extracted with 1 M KCl and titrated with 0.5 M NaOH. Base saturation was calculated as TEB divided by ECEC, multiplied by 100.

2.5 Data analysis

Data were analysed by analysis of variance (ANOVA) to test lithology and depth effects, treating both as fixed factors and the two profiles per lithological unit as replicates. Normality and homogeneity of variance were assessed. Significant means were separated using Tukey's Honestly Significant Difference (HSD) at $p < 0.05$. Pearson correlation assessed relationships among soil properties ($p < 0.05$ and $p < 0.01$). PCA of standardized variables identified the main contributors to soil variability; components were retained using eigenvalues, the scree plot and cumulative variance. High absolute loadings identified influential variables, and scores/loadings were used to assess associations between properties and lithologies. Analyses used SAS 9.4.

3. Results and Discussion

3.1 Soil physical properties across the study area

Table 1 shows the mean particle-size distribution data for the different lithologies, across the study area. The results showed that the mean sand fraction dominated the particle size distribution of soils overlying the different lithologies. Jimoh *et al*. (2019) also recorded high mean sand content (80.50%) in soils of Gombe State University, which is in line with the findings of this study of sand fraction predominance. The dominance of sand particle size in the studied soils might be due to quartz rich parent materials such as granite-gneiss and charnockite (Wilson 2019). Ofem *et al* (2021) opined that sand dominant soils are prone to leaching of basic cations and faced with high infiltration rates as well as loss of nutrients. Mean sand content differed among lithologies ($p < 0.05$), ranging from 52.8% in SSL soils to 90.6% in ALV soils. SSSCI soils also had high sand content (84.6%). Parent-material composition likely contributes to these differences (Brady & Weil, 2017).

Table 1. ANOVA of soil physical and chemical properties over varying lithology.

Lithology	Sand	Silt	Clay	BD	pH(H20)	ECe	OC	TN	AP
		%		Mg/m³		dS m⁻¹	g/kg		mg/kg
SSSCI	84.6a	5.8d	9.5abc	1.72	5.64cd	0.02	2.88c	0.28	2.92
PGB	82.5ab	10.3cd	7.2bcd	1.62	6.27ab	0.05	7.04ab	0.50	5.02
SMS	64.4bc	24.2ab	11.4ab	1.65	5.86bcd	0.03	4.44bc	0.28	4.03
LSS	76.0ab	22.0abc	2.0d	1.52	5.75bcd	0.02	2.46c	0.14	2.74
SLSS	82.6ab	12.2bcd	5.2bcd	1.49	6.03bc	0.04	5.20b	0.31	6.09
BST	71.4ab	18.8abc	9.8abc	1.75	6.67a	0.17	6.82ab	0.50	3.22
SSL	52.8c	32.2a	14.9a	1.75	6.25ab	0.03	4.54bc	0.27	3.43
ALV	90.6a	6.0d	3.4cd	1.61	5.94bcd	0.02	1.32c	0.10	2.74
SSC	83.6ab	7.0d	9.4abc	1.69	5.21d	0.01	1.89c	0.11	3.17
SSS	82.2ab	10.7bcd	6.7bcd	1.53	5.44d	0.05	6.52ab	0.38	6.35
p – value	0.014	0.004	0.039	0.664	0.001	0.296	0.050	0.353	0.236
LOS	*	**	*	NS	**	NS	*	NS	NS
Surface soil	79.42	13.31	7.26	1.63	5.96	0.069	5.09	0.31	4.60
Subsoil	75.84	15.05	9.11	1.67	5.98	0.035	4.12	0.33	3.22
p – value	0.472	0.655	0.280	0.602	0.887	0.278	0.374	0.841	0.055
LOS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Key: SSSCI = Sandstone, Shale, Siltstone, Clay and Ironstone, PGB = Porphyritic Granite and Biotite, SMS = Shale and Mudstone, LSS = Limestone and Shale, SLSS = Shale Limestone and Sandstone., BST = Basalt, SSL = Shale, Sandstone and Limestone, ALV = Alluvium, SSC = Sandstone, Shale and Clay, SSS = Sandstone, Siltstone and Shale, Std Error = Standard error, LOS = Level of Significance, NS = Not Significant, * = 0.05, ** = 0.01, *** = 0.001.

Differences in weathering, clay translocation, biological sorting, erosion and deposition may also contribute to the observed variation in sand content (Usman *et al*., 2017). Sand content did not differ significantly between surface and subsurface samples. Mean silt content ranged from 5.8% to 32.2% and differed among lithologies ($p < 0.01$). SSL had the highest value, whereas ALV, SSSCI and SSC had the lowest values (5.8–7.0%). Silt distribution likely reflects parent-material composition and soil development, as also reported by Abba *et al*. (2016) and Salem *et al*. (2025). Although silt can support crop growth, silt-rich soils may be structurally vulnerable; organic-matter additions can improve aggregation and stability. Clay content was generally low and did not differ significantly with depth. It varied significantly among lithologies ($p < 0.05$): SSL and SMS had the highest values (14.9% and 11.4%), while LSS and ALV had the lowest (2.0% and 3.4%). This agrees with observations from Dadinkowa, Gombe State (Jugulde & Salem, 2023). Soils with more clay and silt can retain more water and nutrients, although their physical behaviour also depends on structure and management (Amalu & Isong, 2018).

Bulk density (BD) in soils across lithologies and depths, did not differ significantly ($p > 0.05$). It is, however, important to note that the range of soil bulk density values obtained across the different lithological units was less than the critical limit for root restriction (1.75 - 1.85 g/cm^3) reported by Soil Survey Staff (2014). The low BD obtained across the study area is typical of coarse-textured soils and will not limit plant growth. The higher bulk density recorded in soils over BST (1.75 g/cm^3) and SSL (1.75 g/cm^3) may be related to the relatively high clay fractions in the respective lithological formations (Oguike and Utin, 2017; Jimoh *et al*., 2025). In a similar study Chaudhari *et al*., (2013) and Tanveera *et al*., (2016) observed the profound effect of soil texture on bulk density and reported an increase in bulk density with increase in sand fraction. However, soils developed over SLSS, having the lowest bulk density, could be attributed to high organic carbon content than soil texture, when compared to the other geologic units. Low BD in the soils imply more pore space for improved air and water permeability. Management practices that will lower bulk densities across all geologic units should be promoted to sustain land productivity.

3.2 Soil chemical properties across the study area

Mean soil pH (H_2O) differed significantly among lithologies ($p < 0.01$), with the highest value in BST (6.67) and the lowest in SSC (5.21). The higher pH over basalt may reflect the basic nature of the parent rock, whereas acidity in SSC soils may be associated with parent material, cultivation and base-cation leaching (Okebalama *et al*., 2024). Overall, pH ranged from moderately to slightly acidic, consistent with findings from other Nigerian soils (Umeugokwe *et al*., 2022). Soil pH is generally within a range suitable for many crops, although lime application should be based on crop requirements and soil-test results. Electrical conductivity ranged from 0.01 to 0.17 dS m^{-1} and did not differ significantly among lithologies or depths. BST had the highest value and SSC the lowest. Surface samples tended to have higher EC than subsurface samples, potentially reflecting evaporation and upward movement of dissolved salts (Jimoh *et al*., 2020). All values were below the 4 dS m^{-1} threshold commonly used to identify saline soils, indicating that salinity was not a major limitation at the sampled sites (FAO, 1993; Soil Science Division Staff, 2017).

Organic carbon (OC) differed significantly among lithologies ($p < 0.05$), ranging from 1.32 to 7.04 g kg^{-1}. Soils developed over PGB, BST and SSS recorded the highest mean values (7.04, 6.82 and 6.52 g kg^{-1}), whereas ALV had the lowest (1.32 g kg^{-1}) (Table 1). Greater plant-material inputs and differences in texture and parent material may explain the higher values. Overall, OC was low, consistent with reports from other Nigerian soils (Abam & Orji, 2019; Afu *et al*., 2022). High temperatures, intensive cultivation and recurring bush burning may accelerate organic-matter decomposition (Okebalama *et al*., 2024). Low OC, combined with sandy texture, can reduce aggregation, water retention and resistance to erosion (Salako, 2003). Total nitrogen (TN) followed a trend similar to OC (Table 1) but did not differ significantly among the ten lithological units or between depths ($p > 0.05$). ALV had the lowest mean TN (0.11 g kg^{-1}), while PGB and BST had the highest (0.50 g kg^{-1}). Values were generally rated low (Soil Science Division Staff, 2017), consistent with reports from Gombe State (Salem *et al*., 2016). Low TN may reflect low organic-matter inputs and losses through leaching, runoff and gaseous pathways. The values were below those reported by Abba *et al*. (2016) and Ibrahim and Umar (2012), highlighting the need to improve organic-matter and nitrogen management. Available phosphorus did not differ significantly among lithologies or depths and was generally low according to Soil Science Division Staff (2017). SLSS, SSS and PGB had the highest values, while ALV and LSS had the lowest. Low organic matter and phosphorus fixation by aluminium and iron compounds in acidic soils may contribute to low availability (Afu *et al*., 2022). The observed values were lower than those reported in several earlier studies of Gombe soils (Abba *et al*., 2016; Jimoh *et al*., 2019, 2025; Ibrahim & Umar, 2012).

3.3 Soil exchangeable bases across the study area

Exchangeable calcium differed among lithologies ($p < 0.05$). BST had the highest mean (19.5 cmol(+) kg^{-1}), whereas ALV and SSC had the lowest (2.15 and 1.70 cmol(+) kg^{-1}). Most units exceeded the critical value of 2.0 cmol(+) kg^{-1}, although SSC was below it (Soil Science Division Staff, 2017). Differences may reflect parent-material weathering, leaching and plant uptake (Fekadu *et al*., 2018; Brady & Weil, 2017).

The mean range of Ca levels found in this study is also considerably higher than values previously reported by Jimoh *et al*. (2019) and Salem *et al*. (2025) but similar to the value

recorded by Jimoh *et al.* (2025) in some soils in Gombe State. However, there was no significant ($p > 0.05$) variation in Ca cmol(+) kg^{-1}). Differences may reflect mineral composition, base-enriched groundwater and

Table 2. ANOVA of soil chemical properties over varying lithology.

Lithology	Ca	Mg	K	Na	TEB	EA	ECEC	BS
	----------cmol/kg----------							%
SSSCI	2.65e	0.72c	0.09de	0.3bcd	3.75f	0.61	4.35e	84.7b
PGB	5.9d	1.73bc	0.28bcd	0.33bcd	8.25de	0.55	8.7de	93.5a
SMS	9.5bc	2.85b	0.33b	0.35bcd	13.03bcd	0.48	13.5bcd	96.5a
LSS	3.2e	0.91c	0.11cde	0.23cd	4.45f	0.17	4.62e	96.1a
SLSS	8.0cd	2.16bc	0.21bcd	0.30bcd	10.6cd	0.40	11.1cd	95.7a
BST	19.5a	5.9a	0.59a	0.76a	26.6a	0.57	27.2a	97.8a
SSL	11.6bc	3.13b	0.31bc	0.5b	15.5bc	0.71	16.3bc	95.5a
ALV	2.15e	0.6c	0.07e	0.25cd	3.06f	0.75	3.81e	81.1b
SSC	1.7e	0.51c	0.09de	0.19d	2.49f	0.69	3.18e	77.79b
SSS	12.9b	3.5b	0.3bcd	0.43bc	17.11b	1.02	18.1b	94.2a
p – value	0.001	0.001	0.001	0.001	0.001	0.559	0.001	0.001
LOS	***	***	***	***	***	NS	***	***
Surface soil	7.84	2.24	0.29	0.38	10.75	0.59	11.35	91.86
Subsoil	8.33	2.46	0.23	0.35	11.34	0.58	11.93	91.12
p – value	0.850	0.778	0.408	0.711	0.864	0.955	0.866	0.805
LOS	NS	NS	NS	NS	NS	NS	NS	NS

Note: SSSCI = Sandstone, Shale, Siltstone, Clay and Ironstone, PGB = Porphyritic Granite and Biotite, SMS = Shale and Mudstone, LSS = Limestone and Shale, SLSS = Shale Limestone and Sandstone., BST = Basalt, SSL = Shale, Sandstone and Limestone, ALV = Alluvium, SSC = Sandstone, Shale and Clay, SSS = Sandstone, Siltstone and Shale, Std Error = Standard error, LOS = Level of Significance, NS = Not Significant, * = 0.05, ** = 0.01, *** = 0.001.

soil content across depths. Calcium was also observed to be the dominant cation on the exchange sites. The prevalence of calcium in the exchange complex is not unexpected, as several authors have reported that calcium dominate the adsorption complex in most soils (Spalevic *et al*., 2017 and Mukaetov *et al*., 2000). Exchangeable Ca contributes to the formation of stable soil aggregates and can react with neutralized mineral and humic acids to produce insoluble Ca-humates (Markoski *et al*., 2018). The mean exchangeable magnesium (Mg) values similar to Ca values varied significantly ($p<0.05$) with lithology, but no observed significant ($p>0.05$) variation between the two depths. Soils developed over BST, SSS and SSL recorded the highest mean Mg values (5.9, 3.5 and 3.13 cmol (+)/kg) while SSC, ALV and SSSCI recorded the least value (0.51, 0.60 & 0.72) (Table 2). One possible explanation for the higher mean magnesium values found in BST soils is a minimal leaching process as a result of high clay content, or nature of the parent material. According to the rating scale of Soil Science Division Staff (2017), the mean Mg range of values was rated high. Kefas *et al*., (2024), also reported high exchangeable magnesium while assessing the influence of topography and lithology on selected soil properties of a differentiated basement complex in northern Taraba state. The nature of the parent material may have an impact on the study's apparent high magnesium content readings (Brady and Weil, 2017). Exchangeable K differed among lithologies ($p < 0.05$) but not depths. BST had the highest mean (0.59 cmol(+) kg^{-1}) and ALV the lowest (0.07 leaching from coarse-textured soils (Esu, 2010). Exchangeable Na differed among lithologies ($p < 0.05$) but not depths. BST had the highest mean (0.76 cmol(+) kg^{-1}), and SSC the lowest (0.19 cmol(+) kg^{-1}). Variation may result from erosion, deposition and leaching (Isola *et al*., 2020). Excess Na can disperse soil aggregates, although the measured values should be interpreted alongside sodicity indices before drawing conclusions about structural risk (Afu *et al*., 2020). TEB differed significantly among lithologies but not between depths. Values were lowest in SSC, ALV, SSSCI and LSS and higher in PGB, SMS, BST, SLSS, SSS and SSL. The high TEB in BST likely reflects its parent material and associated exchangeable-cation reserves. In general, clay and organic matter can increase cation retention (Brady & Weil, 2017).

3.4 Exchangeable acidity, effective cation exchange capacity and base saturation

Exchangeable acidity did not differ significantly among lithologies or depths. The highest mean was recorded in SSS (1.02 cmol kg^{-1}) and the lowest in LSS (0.17 cmol kg^{-1}). Values were rated low by Soil Science Division Staff (2017), suggesting that exchangeable acidity is unlikely to be a major constraint at most sites. Similar findings have been reported for Nigerian savanna soils (Raji & Mohammed, 2000). ECEC differed significantly among lithologies but not depths. BST had the highest mean (27.2 cmol kg^{-1}), while SSC and ALV had the

lowest (3.18 and 3.81 cmol kg^{-1}). Based on Soil Science Division Staff (2017), ECEC was low in ALV, SSC, LSS and SSSCI; medium in SLSS and PGB; and high in BST, SSL, SSS and SMS. Higher ECEC in BST may reflect clay content and mineralogy, whereas low values in ALV may indicate a greater contribution from low-activity clays and sesquioxides (Tan, 2000; Chidowe *et al*., 2014). Base saturation differed among lithologies ($p < 0.05$) but not depths. BST had the highest mean (97.8%), while SSC had the lowest (77.79%). All units were rated high using Soil Science Division Staff (2017). Base saturation is used in soil classification and provides an indicator of the relative dominance of basic cations (Meena *et al*., 2014; FAO, 2014).

3.5 Correlation among physicochemical properties

The correlation heatmap showed strong negative relationships between sand and silt (r = −0.92) and sand and clay (r = −0.84), reflecting the compositional nature of particle-size fractions. Clay was positively correlated with pH (r = 0.378), Mg (r = 0.443) and Na (r = 0.398). Relationships among clay, OC and ECEC indicate that texture and organic matter influence nutrient-retention capacity. Similar links between clay, OC and CEC have been reported in Burundi and Chinese soils (Kaboneka *et al*., 2024; Zhu & Sun, 2024). The positive correlations among Ca, Mg, K and Na indicate that the exchangeable bases tend to vary together. Their strong association with ECEC suggests that soils with greater cation-retention capacity also tend to contain greater quantities of exchangeable nutrient cations. This corroborates Yoni (2024) who submitted that soil management and organic matter accumulation can improve CEC and the retention of exchangeable bases, even in relatively sandy soils. The positive relationship between OC and TN is also agronomically meaningful because soil organic matter constitutes an important reservoir of nitrogen and contributes to nutrient cycling.

Where OC increases, microbial decomposition and mineralisation can contribute to the release and recycling of plant nutrients. The significant positive correlation between organic carbon and total nitrogen aligns with Nnaji *et al*. (2023), who reported that soil organic matter constitutes a major pool of nitrogen and exchangeable cations in tropical soils characterized by low mineral nutrient reserves. Cation relationships revealed that Ca^{2+} and Mg^{2+} were strongly correlated (r = 0.922**), K^{+} (r = 0.816**), Na^{+} (r = 0.828**) and TEB (r = 0.995**), reflecting their common geochemical behavior and potential co-occurrence from the weathering of feldspar and carbonate minerals. The relationship between OC and ECEC is particularly important because organic matter contains negatively charged functional groups capable of retaining positively charged nutrients. Recent evidence from Burundi soils showed that OC was a particularly important predictor of CEC, with models incorporating OC, clay and pH explaining a substantial proportion of CEC variability (Kaboneka *et al*., 2024).

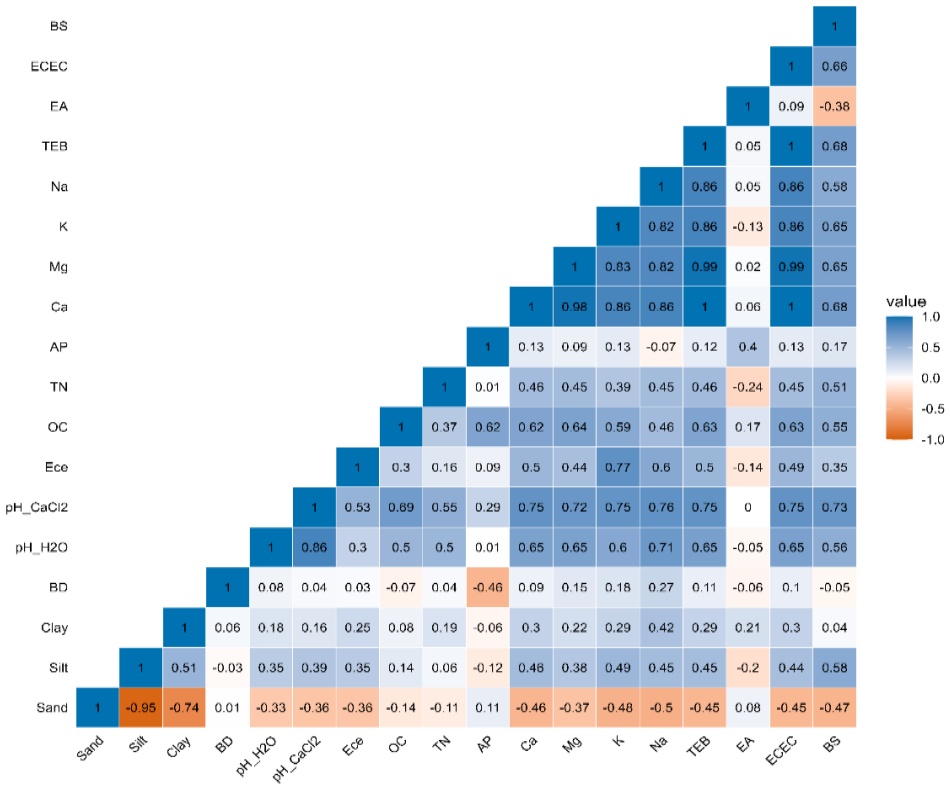

Figure 2. Triangular correlogram matrix (heat map) of soil properties.
Key: Blue indicates positive correlations, brown indicates negative correlations, and values are displayed inside each tile.

3.6 Principal component analysis (PCA)

3.7 Minimum data selection under the lithology

PCA was conducted on standardized soil-property data to identify a minimum data set. Of the 17 variables, the first two components had eigenvalues greater than 1 and together explained 63.7% of the variance (Table 3). PC1 explained 50.3% and was associated most strongly with Mg, TEB, ECEC, Ca, Na, K, pH, TN, BS, EC and OC. PC2 was dominated by texture fractions, particularly sand, silt and clay. Variables with loadings within 10% of the highest loading on each component were considered for selection (Raiesi, 2017).

Table 3. Rotated Component Matrixa of the PCA under the Lithology

PC	Component	
	1	2
Mg	0.896	
TEB	0.894	
ECEC	0.89	
Ca	0.886	
Na	0.864	
K	0.857	
pH H20	0.722	
TN	0.689	
BS	0.656	
Ece	0.576	
Sand		-0.915
Silt		0.877
Clay		0.669
AP		
BD		
OC	0.555	
EA		
Eigen values	8.544	2.298
% of Variance	50.26	13.517
Cumulative %	50.26	63.777

The first two components captured the principal gradients in this soil dataset, where properties reflect combined influences of parent material, climate, topography, vegetation and land use (Brady & Weil, 2017; Rahman *et al*., 2022). Texture fractions and ECEC are useful indicators of soil physical condition and nutrient retention, while bulk density can indicate aeration and resistance to root growth (Maurya *et al*., 2020). PCA scores showed clustering by lithological unit, suggesting that soils formed from similar parent materials shared some physicochemical characteristics (Figure 4). Separation among clusters indicates differences in mineral composition and soil-forming processes, supporting the importance of parent material in soil texture and nutrient availability (Rahman *et al*., 2022).

In the PCA plots, long vectors represented variables contributing strongly to the first two components. BST

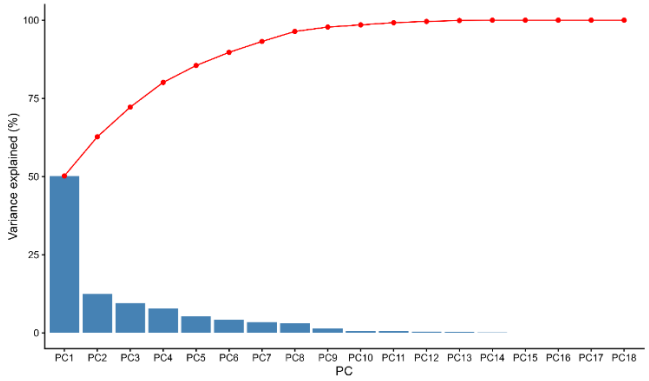

Figure 3. Scree plot showing the percentage of variance explained by each principal component (bars) and the cumulative variance (red line)

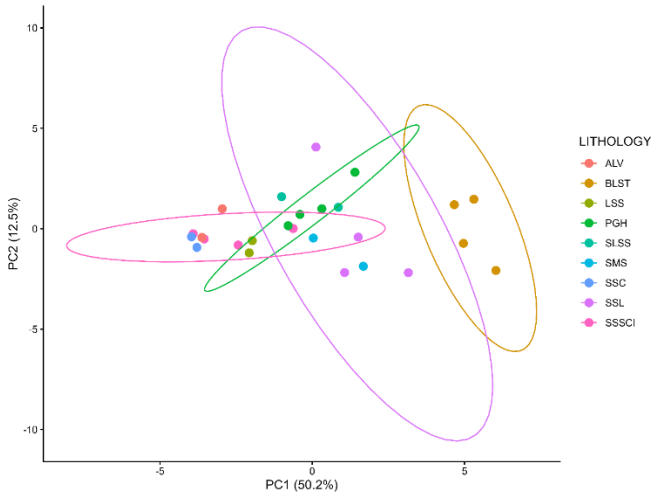

Figure 4. PCA score plot of soil samples colored by lithology. Ellipses represent 95% confidence intervals. BST soils separate strongly along PC1, while PGB soils cluster tightly

samples were separated toward positive PC1, PGB samples clustered closely, and ALV and SSC tended toward negative PC1; SSSCI showed wider dispersion. Variables pointing in similar directions were positively associated, while those pointing in opposite directions were negatively associated. These patterns suggest that lithology contributes to observed soil-property variation, although the interpretation should be considered alongside the sampling design and number of profiles.

The contribution plot identified texture, nutrient status and chemical properties as important variables differentiating soils across lithologies. The scree plot showed a marked decline after PC2, supporting retention of the first two components for summarizing the major gradients. Similar studies identify texture and organic carbon among influential indicators of soil quality (Bünemann *et al*., 2018; Ortner *et al*., 2022).

The PCA biplot showed that texture fractions, bulk density, OC, TN, available P, Na and exchangeable acidity were associated with differentiation among lithological units.

Samples positioned toward a variable had relatively higher values of that property.

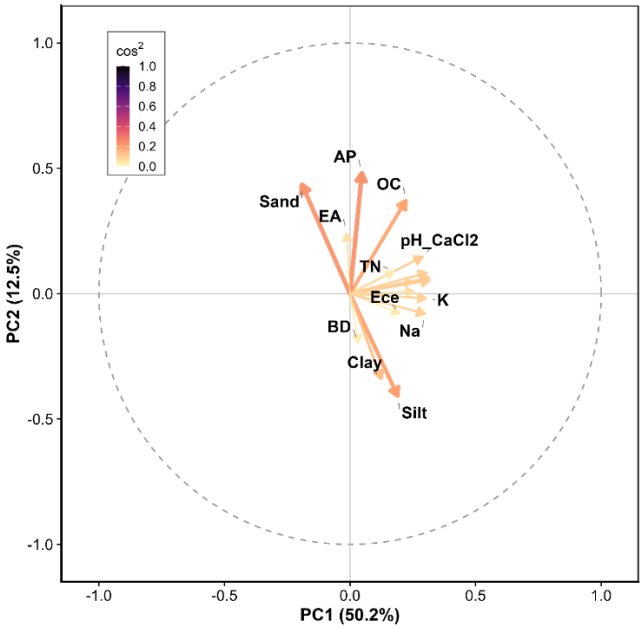

Figure 5. PCA loadings plot showing the contribution of each soil variable to PC1 and PC2. Arrows pointing in the same direction are positively correlated

Overall, the multivariate results support the interpretation that parent material and land use jointly influence soil texture, nutrient dynamics and chemical properties (Brady & Weil, 2017; Rahman *et al*., 2022).

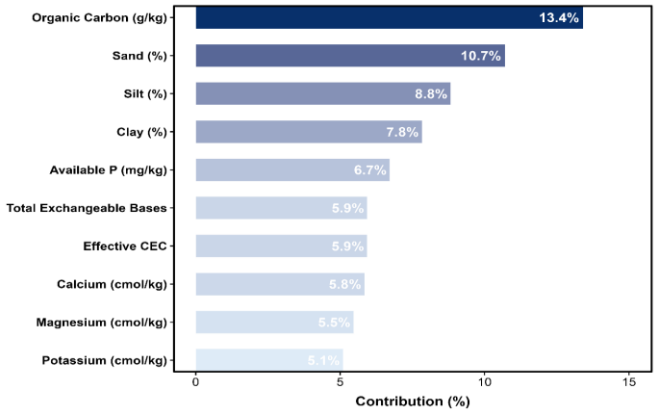

Figure 6. Contribution (%) of the top 10 soil variables to the first two principal components (PC1 and PC2). Bars represent the relative importance of each variable in driving the PCA ordination

4. Conclusion

The study shows that lithological formations are associated with differences in soil physical and chemical properties across Gombe State. Significant variation occurred in particle-size fractions, pH, OC, exchangeable bases, ECEC and BS. Soils over PGB, BST and SSS had the highest OC and TN, while BST and several shale-bearing units had higher exchangeable bases and TEB. ALV soils were sandy and generally had lower nutrient reserves. Soil pH ranged from moderately to slightly acidic, and low EC indicated that salinity was not a major limitation at sampled sites. Correlation and PCA results showed that texture, exchangeable bases, ECEC, pH, OC, TN and BS were important in differentiating lithologies. These findings provide a baseline for lithology-specific land evaluation and nutrient management in the Nigerian savanna.

4.1 Recommendations

i. Match fertilizer, lime and soil-management practices to parent material, prioritizing maintenance of soil organic carbon and nutrient availability.

ii. Use mulching, cover crops, reduced tillage and erosion-control measures on sandy soils to limit nutrient loss and improve soil structure.

iii. Establish long-term soil monitoring and investigate mineralogy and crop responses; strengthen farmer training in lithology-sensitive management.

iv. Manage texture-related constraints, bulk density and organic carbon according to site-specific soil-test results.

Conflict of interest

The authors declare that they have no conflict of interest.

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